Optical phase conjugation by dynamic holography for wavefront restoration in turbid media

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ABSTRACT

Optical Phase Conjugation is a non-linear optical phenomenon that generates a phase conjugate replica of an incident beam. It has been widely used to suppress the effects of aberrations in optical systems such as resonators or image-transmitting optical fibers. In this work, the possibility of using optical phase conjugation as a means of suppressing the effect of scattering in turbid media is analyzed, with the final aim to apply it to biological tissues.

Firstly, light propagation through a slab representing a turbid sample was calculated by solving Maxwell's equations with the Finite-Difference Time-Domain method, in order to preserve all the information about the phase and coherence of the wavefront. The non-linear process that takes place within the phase conjugation mirror is described by coupled-wave theory. A set of simulations was performed, and the results confirm the feasibility of using this effect to compensate the effect of scattering in turbid media.

Subsequently, an experimental set-up was performed. In order to obtain a phase conjugation mirror, degenerate four-wave mixing was achieved by a real-time volume holography configuration. The pulsed laser source was a $Nd3+$:YAG laser at its second-harmonic (532nm). An ethanol solution of Rhodamine 6G was used as a non-linear medium. A lipid-based scattering sample was obtained by a solution of homogenized milk and distilled water, which provided us with an appropriate tissue phantom. The experimental results demonstrate scattering suppression, and constitute some preliminary measurements of an effect with a promising potential for a wide range of applications.

Keywords: Optical phase conjugation, dynamic holography, four-wave mixing, Kerr medium, FDTD, turbid media.

1. INTRODUCTION

Optically turbid media are characterized by a dominant effect of scattering over absorption. Such media include the atmosphere, oceanic water, and remarkably biological tissues. In these media, the scattering coefficient is typically two orders of magnitude higher than the absorption coefficient. Light propagation within them is severely affected by this scattering effect, which is the main limiting factor for a wide range of applications as long as it reduces the penetration depth, worsens the achievable resolution, and decreases received power.

As it is well-known, scattering is due to microscopical inhomogeneities in the refractive index of the medium [1]. The great complexity of the process leads to some statistical parameters that enable us to perform our analysis from a macrostructural point of view. However, it is important to remark that, microscopically, it is not an aleatory process. Elastic scattering is deterministic, and therefore it is susceptible of being reversed.

In order to perform the reversal of the scattering effect and restore a forward-propagating scattered beam to its initial state, it is necessary to generate a back-propagating beam with the same amplitude and conjugated phase, in such a way that it undergoes all the scattering events in the reverse sense. This can be done by means of a phase conjugation mirror

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Optical Interactions with Tissues and Cells XXI, edited by E. Duco Jansen, Robert J. Thomas,
Proc. of SPIE Vol. 7562, 75620A · © 2010 SPIE · CCC code: 1605-7422/10/$18 · doi: 10.1117/12.842179

(PCM). Optical phase conjugation is a non-linear optical phenomenon that generates a phase conjugate replica of the incident beam [2-5]. It is important to note that, while reflection in a conventional mirror would result in accumulative scattering once the beam has travelled backwards, the beam after reflection in the PCM undergoes a time-reversal process that ideally restores it to its initial state.

In this work, optical phase conjugation as a mean of suppressing the effect of scattering in turbid media will be analyzed, both theoretically and experimentally. Firstly, Section 2 describes simulation method used in this work (FDTD). After that, Section 3 includes the results of the pulsed laser beam propagation through a turbid 2D sample. Subsequently, Section 4 presents the experimental set-up used to achieve a phase conjugation mirror, which is based on real-time holography by degenerate four-wave mixing. The results are presented and discussed. Finally, Section 5 summarizes the main conclusions of this work.

2. SIMULATION BASICS

Finite-Difference Time-Domain is a well-known method for performing electromagnetic simulations. It solves Maxwell's equations by a numerical method that requires the discretization of both space and time in the computational region [5-6]. For the scope of this work, it is necessary to keep the information about the phase and the coherence of the wavefront, as long as it is essential for Optical Phase Conjugation. Therefore, FDTD is a particularly appropriate technique for this application. If we take the time-dependent Maxwell's equations for a dielectric medium and we consider a 2D geometry and the TE mode, the resulting equations for the component representations are [6]:

$$\frac{\partial H_x}{\partial t} = -\frac{1}{\mu_0}\frac{\partial E_z}{\partial y}, \tag{1}$$

$$\frac{\partial H_y}{\partial t} = \frac{1}{\mu_0}\frac{\partial E_z}{\partial x}, \tag{2}$$

$$\frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon_0 \varepsilon_r(x,y)}\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}\right). \tag{3}$$

According to FDTD method, se assume that the bidimensional space is discretized according to Δx and Δy, and the time is discretized by Δt. In this way, any function F is discretized as $F^n(i,j) = F(x,y,t)$. According to this basis, Equations 1, 2 and 3 are discretized in both space and time [6], so that they can be calculated as:

$$H_x^{n+\frac{1}{2}}\left(i, j+\frac{1}{2}\right) = H_x^{n-\frac{1}{2}}\left(i, j+\frac{1}{2}\right) - \frac{\Delta t}{\mu_0 \Delta y}\left\{E_z^n(i, j+1) - E_z^n(i,j)\right\} \tag{4}$$

$$H_y^{n+\frac{1}{2}}\left(i+\frac{1}{2}, j\right) = H_y^{n-\frac{1}{2}}\left(i+\frac{1}{2}, j\right) - \frac{\Delta t}{\mu_0 \Delta x}\left\{E_z^n(i+1, j) - E_z^n(i,j)\right\} \tag{5}$$

$$\begin{aligned} E_z^{n+1}(i,j) = E_z^n(i,j) + \frac{\Delta t}{\varepsilon_0 \varepsilon_r(i,j)}\Bigg\{ & \frac{1}{\Delta x}\left[H_y^{n+\frac{1}{2}}\left(i+\frac{1}{2}, j\right) - H_y^{n+\frac{1}{2}}\left(i-\frac{1}{2}, j\right)\right] - \\ & -\frac{1}{\Delta y}\left[H_x^{n+\frac{1}{2}}\left(i, j+\frac{1}{2}\right) - H_x^{n+\frac{1}{2}}\left(i, j-\frac{1}{2}\right)\right]\Bigg\} \end{aligned} \tag{6}$$

It should be noted that the time step Δt is restricted by the spatial discretization width. The stability condition for a 2D geometry is:

$$\Delta t \le \frac{1}{v}\left(\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2}\right) \tag{7}$$

3. SIMULATION RESULTS

The first step developed in this work was the simulation of the process of phase conjugation in a turbid media as a way to assess the feasibility of using a phase conjugation mirror to compensate the effect of scattering. A code was programmed in order to automatically generate the matrix of a random medium with the desired characteristics. The parameters of the medium used in the simulations were chosen according to the typical characteristics of biological tissues [7]. In this way, we consider a medium refractive index of 1.34 (intermediate between the extracellular media and the cellular cytoplasm), a particle refractive index of 1.45 (corresponding to lipid-based organelles like mitochondria), and a particle diameter of 1 μm. The volume fraction of our sample was set to 8%. Figure 1 shows the generated square 2D sample matrix of 50x50 μm. It should be noted that the statistical parameters involved in the sampling of volumetric objects by a plane has been taken into account in order to calculate the radius of each particle.

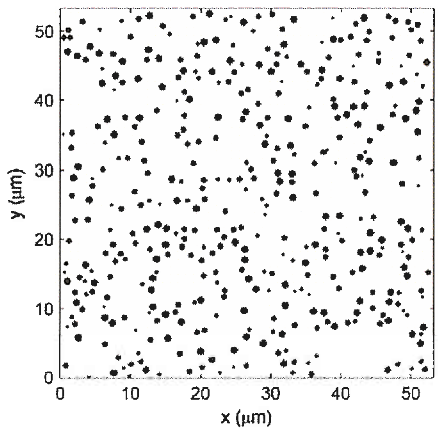

Fig. 1. 2D sample matrix used in the simulations. The particle diameter is 1 μm, and the value fraction is 8%. The dimensions correspond to a sample of 50x50 μm.

In the simulation, an incident light pulse enters the sample by the left, and a Phase Conjugation Mirror is placed in the end-face at right. The results of the simulation can be observed in Figure 2. Firstly, Figure 2a is a still image of the initial forward-propagating pulse. As long as it travels through the turbid medium, it suffers scattering events, and therefore the wavefront suffers a spreading that can be observed in Figure 2b, that shows the forward-propagating scattered beam. Finally, in Figure 2c we show the back-propagating beam after reflection from the PCM and travelling the optical path back to the incidence face. As a result of the phase conjugation process, the scattering effect has been compensated and the pulse has recovered its initial shape. The results of this simulation confirm the feasibility to use phase conjugation as a way to suppress scattering in turbid media, and enables us to further develop our study by experimental measurements.

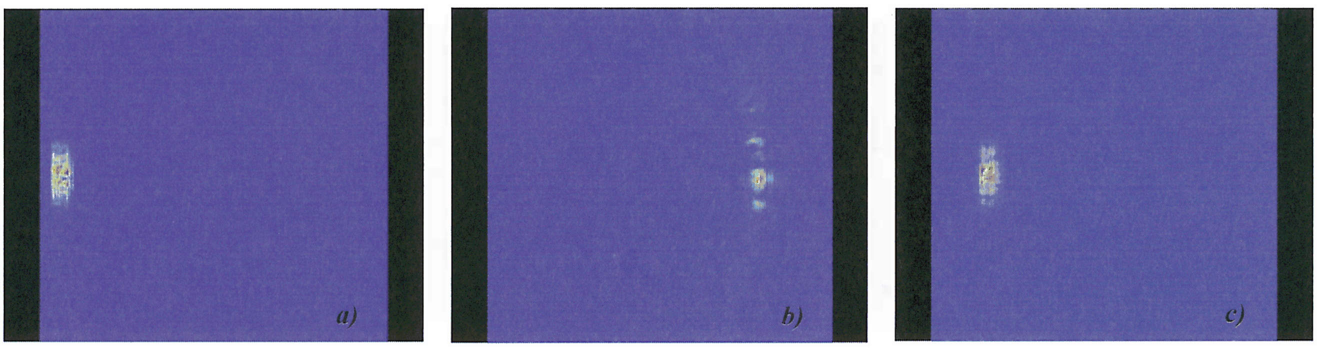

Fig. 2. Light pulse propagation through a turbid sample with a Phase Conjugation Mirror at the end-face. a) Incident light pulse, b) Scattered beam, c) Backpropagation reflected pulse. After reflection in the PCM, the wavefront retraces itself and the scattering effect is compensated.

4. EXPERIMENTAL MEASUREMENTS

The experimental scheme used for obtaining optical phase conjugation was based on a real-time volume holography configuration [8]. It is schematically depicted in Figure 3. The two pump beams are obtained by splitting the initial beam. Then, the probe beam illuminates the sample and interacts with the pump beams in a Kerr medium. Subsequently, a conjugate beam is generated, which travels in the opposite direction to that of the probe beam. The laser source was a Nd^{3+}:YAG laser (Lotis TII, Belarus) using its second-harmonic radiation at a wavelength of λ=532 nm (element 1), with a pulse duration of τ=20 ns. The third-order nonlinear medium was obtained by an ethanol solution of Rhodamine 6G dye (cell 9). The interacting waves were adjusted by mirrors 2, 3, 4, 5, 6 and 7.

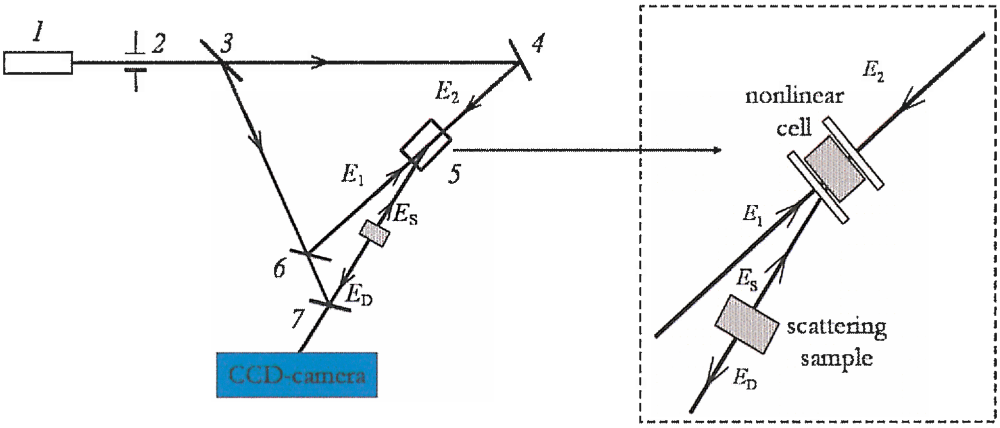

Fig. 3. Experimental setup. 1: Nd:YAG laser operating at 532 nm with 20 ns pulse width. 2: diaphragm. 3,4,6 and 7: mirrors. 5: nonlinear cell (ethanol solution of Rhodamine 6G). The scattering sample shown in the inset is a solution of milk and water. A CCD camera was used for image acquisition.

The scattering sample was a lipid-based tissue phantom. In particular, milk was used as scatterer, as long as it is a readily-available material, and its optical properties have been widely studied. The scattering sample 10 consisted on a 3% solution of homogenized milk in distilled water. We used homogenized pasteurized milk with a fat content of 3.2%. The measured scattering coefficient for pure milk is 42mm^{-1} [7], which is in agreement with previous results [9-10], while the absorption coefficient is considered to be negligible. The anisotropy of scattering typically takes values higher than 0.9, which implies a highly forward-directed scattering and is in good agreement with the usual values for Mie scattering. A cuvette of L=1 mm thickness, was used. The on-axis attenuation for these values is found to be approximately 7.5 dB [7,9-10].

The experimental results are shown in Figure 4. Firstly, the initial laser beam was measured at a distance of 30cm before incidence in the scattering sample (Figure 4a). Next, the milk solution cuvette was inserted in the position indicated in Figure 3. In this step, a mirror was used as element 5, in order to measure the effect of scattering without phase conjugation. Therefore, the measurement is the beam after going through the scattering sample, reflecting in a conventional mirror and passing through milk again. The effect of the scattering produced by the milk lipid particles can be observed in Figure 4b. A broadening of the beam can be appreciated, as well as a degree of heterogeneity within the illumination spot. Finally, the beam obtained with the phase conjugation configuration was measured. The nonlinear cell for phase conjugation generation was inserted as element 9. The resulting beam is shown in Figure 4c. Theoretically, this beam should be equal to that shown in Figure 4a. It can be observed that, indeed, the scattering shown in Figure 4b has been reduced. In this way, the phase conjugation process seems to have effectively compensated the effect of scattering. Nevertheless, we can remark that there exist two differences between both beams. The first one is that the phase conjugated beam has a smaller diameter than the initial beam, probably due to the efficiency of phase conjugated beam generation. As long as it depends on signal beam intensity, phase conjugation generation takes place in the center of the beam with a great efficiency, but decreases far from the center of the beam. The second difference is the presence of background signal, as can be observed in Figure 4c. This is due to the luminescence spectra of the dye solution. Despite these differences, the presented results demonstrate scattering suppression by optical phase conjugation, and constitute some preliminary measurements of an effect with a promising potential for a wide range of applications.

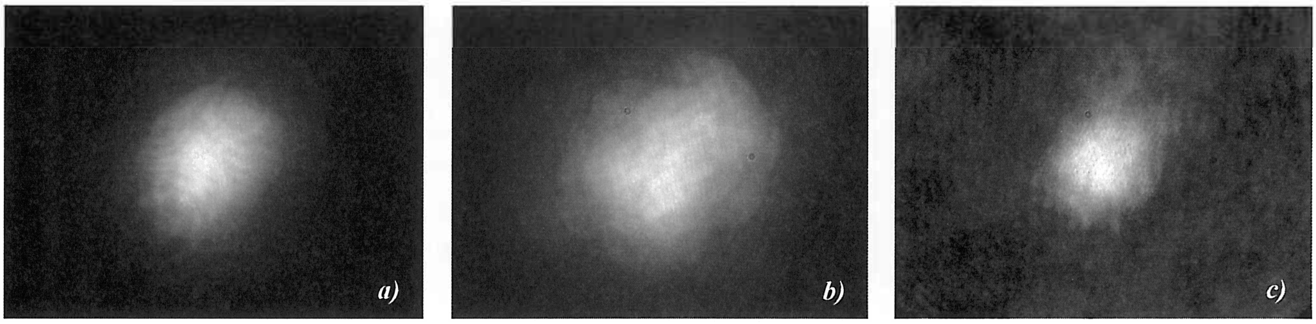

Fig. 4. a) Initial laser beam, b) Scattered beam, c) Resulting beam after phase conjugation.

5. CONCLUSIONS

In this work, the feasibility of using a phase conjugation mirror as a way to suppress wavefront modification by scattering in light transmission through biological tissues has been studied. Firstly, a theoretical analysis has been developed in order to evaluate the scattering compensation in a turbid sample. In order to achieve that, some simulations have been performed by FDTD method. The simulation results show that using a PCM is an effective way to compensate the effect of scattering and achieve beam shape restoration. After that, some experimental results have been presented. Optical phase conjugation has been performed by a real-time holography scheme, using a dye as the Kerr medium and a cuvette with a solution of milk and water as the scattering medium. The results constitute a corroboration of the scattering suppression by phase conjugation. Some experimental issues such as the conjugated signal generation efficiency and the luminescence that takes place in the dye have been pointed to be the main factors affecting the quality of the restored signal obtained throughout the process.

ACKNOWLEDGMENTS

This work has been partially carried out under the project TEC2006-06548/TCM of the Spanish Ministry of Science and Innovation.

REFERENCES

[1] Bohren, C. F. and Huffman, D. R., [Absorption and scattering of light by small particles], John Wiley and Sons, New York (1983).

[2] Zel'dovich, B. Y., Pilipetski, N. F. and Shkunov, V. V., [Wavefront conjugation], Nauka, Moscow (1985).

[3] Saleh, B. E. A. and Teich, M. C., [Fundamentals of Photonics], John Wiley & Sons, New York (1991).

[4] Yaqoob, Z., Psaltis, D., Feld, M. S. and Yang, C., "Optical phase conjugation for turbidity suppression in biological samples", Nature Photonics 2, 110-115 (2008).

[5] Tseng, S. H., Yang, C., "2-D PSTD Simulation of optical phase conjugation for turbidity suppression", Optics Express 15(24), 16005-16 (2007).

[6] Kawano, K. and Kitoh, T., [Introduction to optical waveguide analysis: solving Maxwell's equations and the Schrodinger equation], John Wiley and Sons, New York (2001).

[7] Romanov, O. G., Tolstik, A. L., Ortega-Quijano, N., Fanjul-Velez, F. and Arce-Diego, J. L., "Finite-Difference Time-Domain simulation of light propagation in 2D scattering media", Nonlinear Phenomena in Complex Systems 12, 267-274 (2009).

[8] Tolstik, A. L., [Multiwave mixing in solutions of complex organic compounds], BSU, Minsk (2002).

[9] Danilov, A. A., Dolgushin, S. A., Masloboev, Y. P., Selishchev, S. V. and Tereshchenko, S. A., "Experimental study of optical characteristics of homogeneous highly-dispersive biological medium", Biomedical Engineering 41, 53-58 (2007).

[10] Waterworth, M. D., Tarte, B. J., Joblin, A. J., van Doorn, T. and Niesler, H. E., "Optical transmission properties of homogenized milk used as a phantom material in visible wavelength imaging", Australasian Physical & Engineering Sciences in Medicine 18(1), 39-44 (1995).